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Spatial Reuse and Random Data Hopping in Multihop Ad hoc Networks

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Abstract—Spatial reuse TDMA (time division multiple access) in multihop ad hoc network is a subject of intense research interest for next generation wireless systems. In this paper, the selection of concurrent communication pairs, that utilize the same resources, is formulated as a non-linear mixed integer programming problem. However, it has been found that the solution to this non-linear programming problem is NP-hard. Recently, a random data hopping (RDH) technique applied over a time slot partitioned system has been proposed by the authors as a novel heuristic algorithm. This random data hopping scheme is further studied in this paper for different values of traffic loads, and its performance is evaluated under realistic propagation conditions. It has been found that the variation of the system throughput with the traffic load follows a concave function, and it reaches its peak when the traffic load is around 30%.

Keywords: Spatial reuse TDMA, interference avoidance model, random data hopping.

I. INTRODUCTION

One of the most challenging problems in multihop ad hoc networks is to guarantee a certain quality of service (QoS). This problem is usually considered in the medium access control (MAC) layer. Traditionally, MAC protocols for ad hoc networks are based on dynamic access methods such as carrier sense multiple access (CSMA), e.g., the IEEE 802.11 standard. Although efforts have been made to guarantee QoS in CSMA based MAC protocols, such methods are inherently inappropriate for providing QoS guarantees [1]. The main reason for this inadequacy is the hidden node/ exposed node problem, and exponential back-off schemes, which results in large delays in multihop wireless networks [2]. One of the most important QoS in many applications is delay guarantee, i.e., the upper bound on the time it takes to transmit a message from the source to destination. This is useful when transmitting delay sensitive traffic such as voice or video. One approach where delay bounds can be guaranteed is time division multiple access (TDMA). Unfortunately, this is usually inefficient in sparsely connected networks. However, due to multihop properties, the time slots (TSs) can often be shared by more than one user without conflicts. Therefore, the given resources can be spatially reused in any TS of a TDMA system, in order to increase the network capacity. The idea is to let the spatially separated radio terminals reuse the same TSs when the resulting interference is not severe (exactly how much interference could be tolerated by a receiver, so that it can still detect its desired signal, would depend on the carrier signal strength and on the system specifications). Such a protocol is called spatial reuse TDMA, or STDMA. The gain from spatial reuse must, however, outweigh the increased interference arising from the additional number of transmissions required between the source and destination nodes in the multihop design, in order to achieve an improvement in the capacity.

Spatial reuse in TDMA based multihop packet radio networks was first studied more than two decades back in [3], and was introduced as a collision free access scheme for multihop ad hoc networks. The concept of a spatial reuse channel access schedule for multihop radio networks was formalized by Nelson and Kleinrock [4]. A STDMA scheduler describes the transmission rights for each TS. In the literature, various algorithms for generating reuse schedules have been proposed. Centralized algorithms [5], [6] as well as distributed algorithms [3], [7] have been proposed for multihop ad hoc networks. Most of the early work in the literature have in common that the reuse schedule is designed from a graph-model of the network [8], wherein the radio terminals that are located beyond a certain distance could communicate simultaneously. The graph-based scheduling technique is therefore based on the same principle as the interference-avoidance Protocol Model. Recently, Sinanović et. al. [9] derived the conditions when the spatial reuse of resources would result in higher spectral efficiency for a simple 2-link ad hoc network. Zander [10] proposed an alternative interference model where the signal-to-interference ratio (SIR) is used to describe the interferences in the network. The schedule was defined to be conflict-free if the SIR does not fall below a certain threshold. However, the main disadvantage of such an SIR-based STDMA scheduling is the increased network complexity and the control overhead, as the interference and the SIR has to be calculated at the receiver of every potential communication pair. Hence, in this paper, the multihop network is analyzed under the interference-avoidance Protocol Model. There are two significant contributions of this paper. Firstly, a mathematical representation of the system complexity is provided for a spatial-reuse multihop wireless network. Secondly, the random data hopping technique introduced in [11] has been further studied in this paper for different system traffic load and the variation in the network capacity is computed.
The paper is organized as follows: In section II, the multihop wireless network is described in detail and the optimum system capacity of the spatial-reuse multihop design is presented as a non-linear integer programming problem. The random data hopping technique and the expression for system capacity is explained in section III. The simulation results are provided in section IV, and finally, the conclusion is provided in section V.

II. SYSTEM DESCRIPTION

A. Multihop Ad hoc Network

The multihop ad hoc network is modeled to be deployed in a square-shaped coverage area, \( Z \), with a side length, \( s \). The mobile stations (MSs) are assumed to be uniformly distributed in the given coverage area. A restrictive version of the Protocol Model is considered in this paper, in order to suppress the interference arising from simultaneous communication of several transceiving pairs. As per this model, a circular exclusion region is defined around the receiver of every communication pair [12]. All other concurrently communicating transmission pairs lie outside this exclusion region. The exclusion region of the concurrently communicating pairs do not overlap with each other. This results in several non-overlapping exclusion region circles in the coverage area. The radius of this exclusion region circle, \( r_c \), is a function of the transmission distance, \( d_c \), between the communicating pair, and is given by, \( r_c = d_c(1 + \Delta) \), where \( \Delta \geq 0 \) is the spatial protection margin defined around the receiver. It is shown in [13] that a maximum throughput is realized when the value of \( \Delta \) is close to 1.0. Hence, in this paper, a constant spatial protection margin, \( \Delta = 1.0 \), is considered for all transmission pairs. However, the transmission distance of all the communication pairs are different. Therefore, the radii of all the exclusion region circles are different, which results in non-overlapping of unequal exclusion region circles in the coverage area. On account of this, the ‘optimal throughput calculation problem’ for a multihop ad hoc network with a finite coverage area is now transformed into an ‘optimal unequal circle packing problem’.

B. System Complexity

For any TS, the instantaneous number of simultaneously communicating pairs in the system, \( n_t \), is a random variable that depends on the location of the communicating pairs. The upper bound on the number of simultaneously communicating pairs for any TS, \( L_M \), depends on the area of the coverage area, and more significantly, on the radii of the exclusion region circles. In a practical scenario, the condition for the number of simultaneously communicating pairs for any TS is \( 1 \leq n_t \leq L_M \). If the radii of the \( n_t \) circles are given by \( r_1, r_2, ..., r_{n_t} \), and if \( x_i \) and \( y_i \) indicate the \( X \) and \( Y \) co-ordinates of the circle \( i, i \in \{1,2,...,n_t\} \), then the optimum packing problem of unequal circles can be formulated as follows:

\[
\max(n_t) \quad \text{subject to}
\]

\[
r_i \leq x_i \leq s - r_i \quad \text{for} \quad i \in \{1,2,...,n_t\} \quad (1)
\]

\[
r_i \leq y_i \leq s - r_i \quad \text{for} \quad i \in \{1,2,...,n_t\} \quad (2)
\]

\[
\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \geq r_i + r_j \quad \text{for} \quad i \neq j \quad (3)
\]

\[
0 < r_i \leq s/2
\]

\[
0 < s < +\infty
\]

It should be noted that the conditions (1) and (2) ensure that none of any part of each circle is outside the coverage area whereas condition (3) ensures that there is no overlapping of exclusion region circles. There are usually many different packing configurations which give the same objective function value, and the feasible solutions differ only in the pattern in which the circles are placed [14]. This formulation is a formidable non-linear mixed integer mathematical problem. In fact, it is shown in [15] that for this class of packing problem, it is not only NP-hard to determine the optimal packing, but also, it is prohibitively complex to approximate the optimal packing problem, even for small values of \( n_t \). In addition, in the multihop network design, the maximum packing problem is further compounded by the fact that \( x_i \) and \( y_i \) (the center of the exclusion range circles) cannot be in general freely chosen, but rather depends on the location of mobile/relays. However, this additional condition could be relaxed in the analysis, by the fact that the radius, \( r_i \), of the exclusion region circle could be varied by appropriately selecting the peer node.

III. RANDOM DATA HOPPING TECHNIQUE

In a distributed multihop wireless network, the number of transceiving pairs that can communicate in a given coverage area at any time instant is a function of the position of selected nodes in the system. Fig. 1 (a-b) shows two cases in a spatial-reuse multihop ad hoc network, where the exclusion region circles are distributed within the bounded coverage area. Case (a) represents a scenario where more number of pairs could communicate simultaneously, but there are no more transmission pairs for communication. In case (b), the placement of the communicating pair of nodes are such that no more nodes
could transmit data in the particular time instant. However, it
can be seen that an efficient placement of nodes results in an
increased number of concurrently communicating pairs for any
time instant. In this technique, each time slot is first partitioned
into several mini TSs and the mini TS over which the partic-
ular transmission pair communicates is randomly varied [11].
Hence, the number of concurrent communication pairs over
each mini TS gets altered randomly. This is the underlying
principle behind the random data hopping technique.

A. Multihop Network Model

In a spatial reuse multihop network model, the power at the
receiver of the \( i \)th transceiver pair, separated by a distance, \( d_{ci} \), is found from a generic pathloss model as:

\[
P_R = P_T - (k_1 + 10\alpha \log_{10}(d_{ci})) \text{ dB} \tag{6}
\]

where \( P_T \) is the transmit power, \( \alpha \) is the pathloss exponent and \( k_1 \) is a propagation constant. A constant transmit power is
assumed for all the nodes in the system. For each of the \( n_t \) simultaneously communicating pairs at any time slot, \( t \), the
remaining \( n_t - 1 \) simultaneous communicating pairs act as interferers. Therefore, the carrier-to-interference ratio, \( \gamma_{it} \), of the \( i \)th communicating pair at \( t \)th TS is given by

\[
\gamma_{it} = \frac{10^{P_T/10} 10^{-\left(k_1 + 10\alpha \log_{10}(d_{ci})\right)/10}}{\sum_{j=1,j \neq i}^{n_t} 10^{P_T/10} 10^{-\left(k_1 + 10\alpha \log_{10}(d_{int_{ij}})\right)/10}} \tag{7}
\]

which simplifies to

\[
\gamma_{it} = \frac{d_{ci}^{-\alpha}}{\sum_{j=1,j \neq i}^{n_t} d_{int_{ij}}^{-\alpha}} \tag{8}
\]

where \( d_{int_{ij}} \) is the distance between the receiver of the \( j \)th communicating pair and the transmitter of the \( j \)th communicating pair. The distance between a desired receiver and an unintentional transmitting entity is given by \( d_{int_{ij}} \geq (1 + \Delta)d_{c} \). The expression for \( \gamma_{it} \) can be lower bounded by assuming that all the interfering nodes are at the circumference of the exclusion region itself. In this case, all the interfering transmitters would be at the closest possible distance from the intended receiver. Hence, this would model the worst-case interference scenario. For such a scenario, the distance of all the transmitting interferers from the receiver of the \( i \)th communicating pair would be given by \( d_{int_{ij}} = (1 + \Delta)d_{c} \). The carrier-to-interference ratio, \( \gamma_{it} \), in eqn. (8), can therefore be lower bounded as follows:

\[
\gamma_{it} \geq \frac{(1 + \Delta)^{\alpha}}{n_t - 1} \quad \forall \ i \in \{1, 2, ..., n_t\} \tag{9}
\]

The average system capacity for the wireless network is calcu-
lated from the expected values of \( \gamma_{it} \) and \( n_t \).

B. Calculation of System Capacity

The Shannon equation for system capacity is used to derive
the equation for aggregate system capacity. For a continuous
transmission by a communication pair, the Shannon capacity
of the system is given by:

\[
C_s = \log_2(1 + \gamma) \text{ bps/Hz} \tag{10}
\]

where \( C_s \) indicates the Shannon capacity of the communication
link, and \( \gamma \) is the carrier-to-interference ratio, at the receiver of
the communication link. However, the performance measure
for the multihop ad hoc network that is considered in this
research work is the aggregate system capacity of the network.

In a multihop system, there are several communication pairs
per link. Each of these pairs would communicate for only one
of the \( T \) TSs. Hence, each of the pairs would contribute to
the capacity for only one of the \( T \) TSs. In addition, since the
TDMA frame has \( T \) TSs, the calculation for system capacity
is performed for all \( T \) TSs. Apart from that, in general, \( n_t \) is
different for each TS. Hence, while calculating the aggregate
system capacity, the capacity has to be calculated for each of the
\( n_t \) concurrently communicating pairs.

It is to be noted that the total area occupied by the exclusion
regions of all the communicating pairs for any time instant, \( t \), is given by

\[
A = \sum_{i=1}^{n_t} B_i \tag{11}
\]

Packing of non-overlapping unequal circles, however close,
would always result in some unoccupied area between the exclusion range circles. Hence, the sum of the area of the exclusion range circles, \( A \), given by eqn. (11) would always be less than the coverage area, \( Z \), considered in the system, i.e., \( A \leq Z \). It should be noted that scaling by the term \( Z \) is more appropriate than scaling by the factor, \( A \). Hence, in order to calculate the aggregate system capacity for a given coverage area, the equation for the system capacity is scaled by the factor, \( Z \).

The equation for aggregate system capacity is written as
follows:

\[
C = \frac{1}{ZT} \sum_{t=1}^{T} \sum_{i=1}^{n_t} \log_2(\gamma_{it} + 1) \text{ bps/Hz/km}^2 \tag{12}
\]

A unit coverage area is considered throughout in the system
design for the multihop ad hoc network. Also, in the calculation of eqn. (12), it is assumed that all the nodes have sufficiently
time buffer. Hence, all the pairs of a communicating link would communicate, either in the given time frame or in subsequent
time frames. Therefore, all the communicating pairs contribute
to the system capacity.

C. Effect of Log-Normal Shadowing

In order to study the performance of the random data hop-
ing technique under realistic pathloss conditions, a lognormal
shadowing with a standard deviation of 4 dB is considered. In
the presence of lognormal shadowing, the received power, \( P_R \),
and the carrier-to-interference ratio, \( C/I \), given in eqn. (6) and
eqn. (8) would be modified as follows:

\[
P_R = P_T - (k_1 + 10\alpha \log_{10}(d_{ci}))\text{ dB} \tag{13}
\]

\[
\gamma_{it} = \frac{d_{ci}^{-\alpha}}{\sum_{j=1,j \neq i}^{n_t} d_{int_{ij}}^{-\alpha}} \tag{14}
\]

where \( P_R \) is the received power, \( \alpha \) is the pathloss exponent and \( k_1 \) is a propagation constant.
increase in the average system throughput. This increase results from a number of occasions when a high number of communicating pairs are responsible for the placement of nodes. This results in an increased number of interfering MSs. The random data hopping technique produces an inherent randomness in the assignment of MSs that have data to transmit depending on their traffic pattern. It should be noted that at any node, the data is transmitted to the immediate receiver after employing the random data hopping technique. This is because, for less traffic, the total interference experienced by any communicating receiver is less as compared to the high traffic scenario. Hence, the C/I experienced at any receiver is higher. This results in an increase in the average system capacity for a multihop network with a low traffic load, compared to a multihop design with a high traffic load. Fig. 2 shows that for a system with a 100% traffic load, a maximum increase in the average system capacity that could be obtained by employing the random data hopping technique would be around 16%. When the traffic load is less, the improvement obtained by the random data hopping scheme is higher. For example, at 30% traffic, a increase of around 31% is observed at 100 TSs per time frame. It can also be observed from Fig. 2 that for high traffic load (80% and 100% traffic in Fig. 2), the system capacity saturates at around 100 TSs per frame, compared to low traffic load (30% and 40% traffic) where the throughput does not saturate at even 100 TSs per frame. The simulation results for the lognormal shadowing scenario are plotted in Fig. 4. It can be observed that, even in the presence of lognormal component, the RDH technique shows an improvement in the performance. For 30% traffic load, a maximum improvement of 21% is observed compared to the 31% improvement in the absence of log-normal component. This is because, the interference experienced by any receiver node due to an interfering transmitter located at a much far-off distance could be higher due to the lognormal component, which in turn deteriorates the performance of the RDH algorithm.

At this stage, it should be mentioned that an intelligent routing technique in the multihop ad hoc network might provide still better result. However, this paper does not focus on the benefits of employing smart routing techniques. In order to further study the effect of traffic load, the variation of system capacity with the traffic load is observed for different values of TS partitions and is shown in Fig. 3.
that, irrespective of the number of TSs per frame, the variation of system capacity observed a similar pattern. Initially, the capacity increases with increasing traffic and attains a peak for a certain value of traffic load (around 25% - 30%), after which the system capacity decreases. This indicates that there exists an optimum value of traffic load (i.e., an optimum ratio between the communicating nodes and the relay nodes where the system capacity is maximized).

V. CONCLUSIONS

In a distributed multihop network with no central controller, it is an NP-hard problem to find an optimum allocation scheme that would spatially reuse the resources, and thereby, maximize the system capacity. A simple mechanism that has been found to efficiently assign the radio resources is the random data hopping algorithm. In this technique, the TS granularity of the TDMA frame is first increased by reducing the duration of each TS. A random data hopping scheme, is then implemented, whereby, the TS over which the transmission pair communicates is varied randomly. In an important result, it has been shown through computer simulations that an increase in the TS granularity, combined with the random data hopping technique provides a significant increase in the performance, which varies with the traffic load of the system (31% gain for a traffic load of 30%, as compared to 16% gain for a traffic load of 100%). However, irrespective of the number of TS partitioning, the peak gain of the random hopping method is attained for a traffic load varying between 25%-30%. This provides an important direction for future research - finding an analytical expression for the optimum traffic load that would maximize the performance of the random data hopping algorithm, similar to the ALOHA system.

REFERENCES